LOW COST ATMOSPHERIC PROBE MISSIONS TO THE OUTER PLANETS

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Abstract

Outer planet probe missions are part of the on-going Mission and Tethnology Roadmap effort to define the framework for the future NASA Solar System Exploration program. The potential science returned from the probe missions is in the break through category and enabled by advanced technologies described in the paper. Technology needs are predicted on mission/system studies carried out over the past several years. A baseline mission/system design is described to which the technology needs can be related.

INTRODUCTION

Missions such as the atmospheric probe missions to the outer planets participate in the quest to explain the formation and evolution of the Solar System and the Earth within it. The probe missions described in this paper seek: understanding of the origin of the solar nebula and forces that formed Earth and the other planets; to determine the evolutionary processes that led to the diversity of Solar System bodies and the uniqueness of the planet Earth; and to use the exotic worlds of our Solar System as natural science laboratories. Broad science objectives of these missions have been set by the Solar System Exploration Road Map effort carried out by NASA over the past year:

- diversity and dynamics of planetary atmospheres
- global circulation of planetary atmospheres
- bulk composition of Solar System

The key to low cost atmospheric probe missions to the outer planets is low probe mass and short flight time to the target planet. Microtechnology and advances in thermal control/heat shield technology allow both objectives. Application of microtechnology to a Saturn Probe mission using the Cassini Orbiter for entry science data relay purposes was investigated in 1993 and 1994 (Wallace et al, 1994). The material this reference was based on was prepared by the Saturn Mini-Probes Team, made up of members from Jet Propulsion Laboratory (JPL), Martin Marietta Corporation, Hughes Space & Communications Company, Ames Research Center, NASA Headquarters, University of Hawaii, and University of Arizona. That effort explored the potential to reduce probe mass and cost by an order of magnitude. The conclusion was that, given expected advances in the key technologies, such dramatic mass and cost reductions appeared feasible. The application of advanced technologies to missions to all four of the Gas Giant outer planets was subsequently initiated about a year later in an independent study carried out at JPL with the support of the NASA Outer Planet Science Working Group (OPSWG), and consultation from Ames Research Center. This paper reports on the results and conclusions from that study as well as describing the new mission technology needs for the resulting mission/system designs. A companion paper, complementary to this paper on outer planet atmospheric probes, describes system design issues for a flyby mission to the outer planets and is also included in Conference Session A3., Exploration Of the Solar System (Staehle et al, 1996).

MISSION SCOPE & KEY TRADES

Scope

Cost drivers and technology needs are identified for the missions. Mission objectives are to probe depths > 10 bars for Jupiter, > 20 bars for Saturn, and 50 to 100 bars for Uranus and Neptune, with measurements every one sixth scale height. Time history measurements of composition and atmospheric structure (pressure, temperature, and wind velocity) are required. Missions are considered for launching in the 2004 to 2010 time period with a preference shown for the potential of a low cost multi-planet mission program. Four launches over six years or less is considered desirable to allow heritage and low cost.

Key Trades

Delivery mass Vs flight time is a key trade in selecting technology and constraining cost. Direct ballistic, planetary gravity-assist, and solar electric propulsion trajectory analyses were carried out. Other trades involved science return Vs. system trades, among these being: measurement profile (payload mass/cost and data rate), power require ments (probe power capability and mass), penetrat ion depth (telecommunication trades, e.g., frequency, range, mass), and number of probes to each target planet.

BASELINE PROGRAM. DESCRIPTION

Trajectory Selection

The Jupiter gravity-assist opportunities for launches in 2006 arrd 2007 to Neptune and Uranus allowed grouping the launches for low cost arrd relatively short flight times: > 150 kg (single probe delivery) to Uranus and Neptune in 5.7 years and 8.6 years respectively, both launched by the Delta I (7925)/STAR 30 BP low cost launch vehicle. Shorter flight times for Jupiter and Saturn missions result from launches in 2004 and 2005. See Figures 1 & 2 for target planet delivery mass Vs. flight time plots.

Probe. Payload

The OPSWG recommendation for a high science return strawman probe payload included the instruments listed below - the mass, power, and bits-per-sample requirements were arrived at with the help of the OPSWG, the JPL Advanced Projects Design Team, and other members of the planetary science community:

Instrument	Mass /	Power /	Bits per Sample
- Mass Spectrometer	1.0 kg /	10 W /	50,000
- Atm. Structure	0.5 kg /	3 W /	?00
- Solar NFR	0.5 kg /	1 W /	100
- He Abundance	0.5 kg /	1 W /	40
- Nephelometer	~ 0.5 kg /	~ 3 W /	~ 200
- 0- P H_2 Detector	0.5 kg /	2 W /	40
(deployment mechanisms)	(0.5 kg)	-	-
Total	4.0 **kg**	**/ 20 W**	**/** ~50,000

Multi-Probe Program

The Table below summarizes the performance characteristics of the full four-planet program with delivery of four atmospheric probes to each target planet. The mass of each probe resulting from the application of micro-technology is about 80 kg for Jupiter and 55 kg for Saturn, Uranus, and Neptune. The probe mass difference is due to the higher heat shield mass required for the significantly higher entry speeds at Jupiter. The injection masses listed below are based on full system by system designs with the range due to uncertainties in the multi-probe integration and deployment implementation

Targets	Launch	Inj Mass (kg)	Launch Vehicle	Trajectory Mode	Flight Time
Saturn	**2004**	310	Delta III	DVEGA	**4.5** yrs
		430			4.8 yrs
Uranus	2007	299	Delta III/Star 48	Jupiter	5.5 yrs
		419		Gravity Assist	6.7 yrs
Neptune	2006	299	Delta III/Star 48	Jupiter	8.0 yrs
		419		Gravity Assist	11.0 yrs
Jupiter	2005	444	Delta II (7925)	DVEGA	-- 4.5 yrs
		540			

Costing

Both top down and preliminary bottom up cost estimates for the Baseline four-planet (four probes to each planet) program concept were produced. The cost estimate came to less than $1 billion ($935 M), including: development (Phases C & D), four launch vehicles, pre-['reject development (Phases A & B), and mission operations (Phase E). Non technology areas for cost reduction were identified that could potentially reduce total program cost by about $100 M - within the error of tile Baseline cost estimation. The development cost (Phase C & D) per mission isallout$135 M. This compares with a cost of $300 M to $400 M pcr single probe mission using pre-microtechnology probes of mass near 300 kg.

GENERAL TECHNOLOGY NEEDS

A priority of the studies conducted to date has been to identify technology advances required **for low mass, low cost probe missions. Technologies** which **could reach maturity** in the next 4 to 6 years were identified and **have been recommended** for funding.

Many emerging and anticipated developments in microelectronics will be applicable to probe design. These include new families of integrated, light-weight science instruments, multi-chip-module electronics (MCMs) and lithium chemistry batteries . In particular, development of a light weight mass spectrometer is the primary requirement for scientific investigation of outer planet atmospheres. Other technology areas include development of low temperature electronics to minimize thermal control requirements and electric power generation using the planetary atmosphere to drive aerodynamic devices such as turbines. This latter development could significantly augment the limited battery power available and allow data transmission from deeper within planetary atmospheres.

Advances in areas which reduce the probe and carrier vehicle mass are summarized in Table 1. A key element in **probe mass reduction, the entry** thermal **protection,** is discussed in the next Section.

TABLE 1. Summary of New Technology Needs

Probe Technology Needs	Description
Science Instrument Package	High resolution mass spectrometer, gas sensors, refractive index, temp/press/accel,solar NFR, sound velocity; goal of 3 kg, 15 W
Light Weight Heat Shields & Aeroshells for Entry Vehicles	Goal of <20% of total vehicle mass at Saturn, <15% at Uranus and Neptune (see Section V)
Parachutes, Ballutes and Other Atm Braking Devices	Goal of reducing mass by >50%; ballute development especially promising
Integrated Packaging of Electronics & Sensors	Combined electronics & optics for sensor packages; MCMs, internal connections to reduce cabling; goal Of 10-50?(. mass reduction
Low Temperature Electronics	Operate at low power/low temperature (-20 to -100 C) during quiet cruise; power-up at encounter; ability to test at room temperature
Radiation Tolerant Electronics	>200 krad, low cost parts required for high-radiation environment at outer plants
Sleep Mode	Low power mode required for probe and carrier; reduce power requirements by 50-90%, enable low-power radioisotope sources
Power and Thermal Control Heat Generator	RHU/Thermoelectric Generator providing 1 W thermal and >34 mW electric each, goal of <100 g each
Aerodynamic Power Generator	Turbine driven generator power source during atmospheric descent; goal of 100 W weighing 1.5 kg; provides primary power during descent; allows deeper penetration into atmosphere
L-band Relay to Carrier	Highly integrated transmit system with 15 W SSPA (>30% eff.), encoder, modulator; switchable data rates
Lithium Chemistry Batteries	Hi energy density, long shelf-life, goal of >135 Whr/kg & >270 Whr/l
Low Mass and Volume Electronics	Enhanced MCM including power handling electronics with a goal of 250-1100 W/kg and 6-30 W/cm^3

TABLE 1. Sumt ary of Now Technology Needs (Continued)

Carrier Technology Needs	Description
Doop Space Powor Systems	•Low mass, Low Intensity/Low Temperature (LILT) solar array for Saturn distances, augmented by Power-Stick •Radioisotope for Uranus & Neptune, Thermal-Photo Voltaic Generator with a goal of 125 W weighing <5 kg
L-band Relay to Probe	Integrated receiving system with low-noise front end, demodulator, decoder
Deep-Spaco Transponder	X-band Deep-Space Tiny Transponder, goal of 0.5 kg, < 8 W

PROBE HEAT SHIELD TECHNOLOGY

The probe heat shield mass is a significant proportion of the total probe ma.% (15% to 25% for Saturn, Uranus, Neptune probes, depending on the technology selected), and is therefore highlighted here as an enabling technology. Lower heat shield mass ratios will allow lower flight times, more science return, and enable higher mission success in general.

The anticipated atmospheric entry velocities at Saturn, Uranus, and Neptune will be roughly one-half of the 48 km/s speed of the Galileo probe relative to Jupiter's rotating atmosphere. The atmospheric composition of all three planets are very similar to Jupiter with varying ratios of the hydrogen-helium ratios. The Jovian atmosphere is 89% hydrogen and 11% helium, while Saturn's is 95%-5%, Uranus' is 85%-15% and Neptune's is 81 Y.-19Y0. For initial studies of entry probe heat shield mass estimates, it has been proposed **that** maximum **use be made** of the Galileo probe technology base and that the same basic configuration be used for these outer planet entry vehicles.

For review, the Galileo entry shape was a 45° cone shape with a spherically blunted nose having a maximum base diameter of 1.265 m. The Jovian Galileo probe, designed for the most severe of all planetary entry environments, was protected by an ablative heat shield consisting of carbon phenolic material. This material has significant heritage from earth-based, ballistic missile programs over the decades and is well suited for high-pressure, high heating rate entry environments. As previously mentioned however, the Galileo entry was far more severe than any terrestrial entry scenario, which resulted in the thermal protection system (TPS) for Galileo being designed with a 50% safety margin based on the best available conservative predictions (late 1970s), As such, the ablator material for Galileo comprised approximately one-half of the entry mass of the probe. Future outer probe missions will be driven to minimize the TPS heat shield mass fraction in order to provide sufficient capability to the scientific payloads.

Recent studies of TPS mass fractions for Saturn, Uranus, Neptune (S/U/N) entry probes used the Galileo technology base to estimate the heat shield masses for a range of entry velocities. The anticipated entry velocities will result in a heating environment that is connectively dominated heating in the boundary layer (with peak turbulent convective heating rates exceeding 6 kW/cm^2 at the highest entry speeds) in contrast with the radiatively dominated shock layer heating conditions for the high-velocity entry of the Galileo probe (with peak heating conditions a factor of 2-5 greater than the S/U/N entries). As a result, the heat shield mass fractions for the S/U/N probes should be significantly less than Galileo. For Saturn entry probes entering with a relative velocity range from 27-32 km/s, the TPS mass fractions vary from 0.18 to 0.28. For Uranus and Neptune entries, the anticipated relative entry velocity varies from ?2-26.5 km/s and the resulting TPS mass fractions are 0.08 to 0.15 of the entry vehicle mass. It is instructive to compare the **heat** shield mass fractions with those of several other probes. The Pioneer-Venus large probe had a heat shield mass fraction of about 0.10 and discarded its heat shield at subsonic speeds. The Pioneer-Venus small probes had heat shield mass fractions of about O. 13; however, the heat shields were not discarded during the lengthy descent through the atmosphere. The forebody heat shield mass fraction of the Galileo probe is 0.43 and the heat shield is designed to be dropped at subsonic speeds.

It is entirely possible to consider various improvements that could result in significant reductions of TPS mass fractions of the S/U/N probes. The recent Galileo entry has provided actual TPS response data that will provide direct correlations of ablator material response to the entry heating environment in the hydrogen-hcliurn atmosphere. Detailed analysis of this data will provide enhancements to current predictive models of aerothermal flowfield environments and ablator material response. This analysis should be applicable to other outer planet entry probe scenarios and thus serve to reduce uncertainties in estimating the required ablator thicknesses. Furthermore, a new class of TPS materials called lightweight ceramic ablators (LCA) is under development and receiving flight certification for planetary entry missions. One type of material, Phenolic Impregnated Carbon Ablators (PICA), has potential applications to outer planet probe missions. PICA uses a preformed fibrous carbon substrate that is infiltrated with a phenolic resin. PICA has superior thermal conductivity to carbon phenolic and it has an overall material density that is a factor of 5-6 less than the carbon phenolic that was used on Galileo. This material shows promise and future mission studies are planned to further investigate the potential l"PS mass fractions of Saturn, Uranus, and Neptune entry probes using advanced lightweight ablators.

CONCLUSIONS

Mission, systems, and cost trade studies were performed at JPL, applying the described advanced technologies (Table 1.) to enable low cost outer planet probe missions by reducing system mass anti cost. Particularly important to the system design was the application of advanced heat shield technology for the probes - described in the previous Section. Innovative modes were found for achieving communications from great atmospheric depths, using the probe descent itself to generate electrical power by means of an aero turbine. The OPSWG defined high-value science payloads for atmospheric probes to the four Gas Giant outer planets. Studies to understand the mission sensitivity to advances in technology are continuing, as well as continuing definition of the best outer planet probe program to meet the nations needs. It is clear from the studies carried out to date that these probe missions will only be implemented if the appropriate technologies are brought to readiness for them.

Acknowledgment

1 he mission, systems, and cost trade & design studies that resulted in the data on which most of **this paper is based were** performed **by the** JPL Advanced F'rejects **Design Team and** members **of the** NASA Outer Planet Science Working Group, chaired by William B. Hubbard of the University of Arizona

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Reference

1. Wallace, R. A., et al, "Saturn Probe, Science & Engineering Feasibility", Paper No. 0403P, IAA International Conference on Low Cost Planetary Missions; Laurel, Maryland; April 12 through 15, 1994.

2. Staehle, R. L., et al, "Pluto Express: Advanced Technologies Enable lower Cost Missions to the Outer Solar System and Beyond", Space l-ethnology & Applications International Forum (S1 AI F-97), 1 st Conference on Future Space Science & Earth Science Missions, Session A3. Exploration of the Solar System; Albuquerque, NM; January 26-30, 1997.

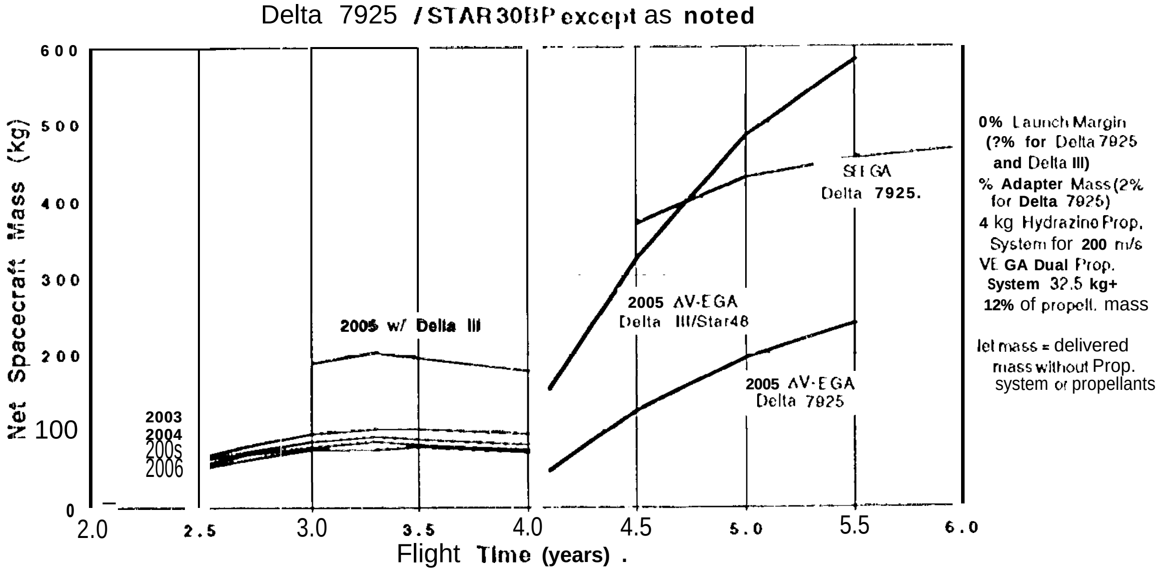

FIGURE 1. Saturn Delivery Mass Performance

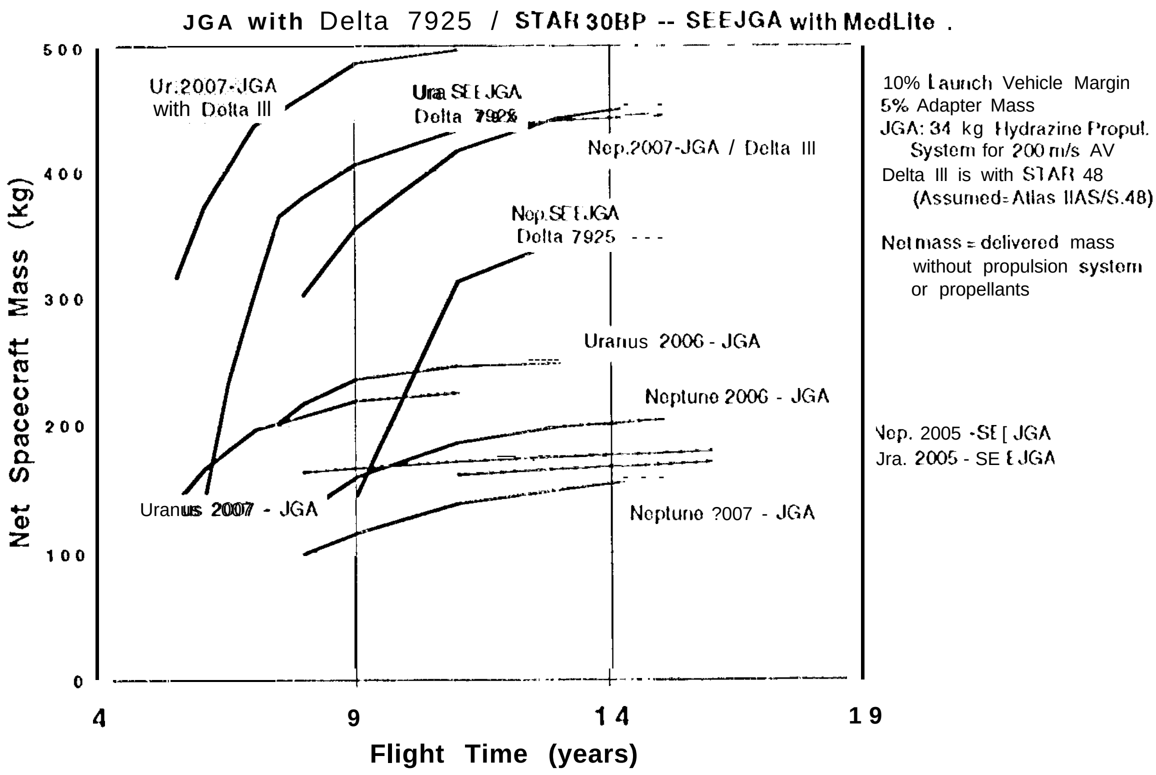

FIGURE 2. Uranus& Neptune Delivery Mass ['performance